Application of Earth Sciences Products for use in Next Generation Numerical Aerosol Prediction Models

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LONG-TERM GOALS

The long-term goal of this project is to devise a forward modeling system to characterize and predict clear sky radiation fields through the harvest of a number of preexisting basic research programs funded by Navy and other government agencies (NASA, NOAA, DOE, etc.). With an aerosol radiance forward model, we will be able to combine model aerosol background fields from the NRL Aerosol Analysis and Prediction System (NAAPS) and Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS®[1]) with near real time satellite surface and aerosol products to generate a real-time aerosol analysis field for aerosol model initialization. Through this aerosol data assimilation system, we will be able to advance a number of US Navy Applied Science needs in the areas of improved Electro Optical (EO) propagation prediction and aerosol meteorology interaction. Further development of the Navy's atmospheric constituent data assimilation system depends on our focused efforts, including the utilization of a number of satellite-based products. The evaluation and characterization of relevant satellite products, including passive aerosol retrievals, lidar profiles, and other relevant cloud and precipitation products, does require substantial effort, but will feed into a system for the calculation and improvement of atmospheric radiance fields from Navy meteorological data feeds. Our work will also enable quasi-operational computations of aerosol impacts on atmospheric diabatic heating rates and surface fluxes, as well as provide a significant upgrade to the Navy's aerosol data assimilation system through the inclusion of a number of additional satellite sensors. Lastly our efforts will significantly improve source and sink functions for Navy, as well as outside aerosol models, and prepare for expected data gaps in the early 2010's.

OBJECTIVES

Scientific objectives of this project over its lifecycle were tightly aligned with the long-term goals listed above, and can be broken down into the following categories by relative project order a) model data assimilation and initialization; b) source functions; c) radiative transfer; d) synthesis and scale independent integration. In the third and final year of the project, focus has surrounded the transition of data assimilation and its use for improving source functions. Specific objectives and status are as follows:

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- Develop quality-assurance and quality-control procedures for over-land MODIS aerosol product and AVHRR, and expand assimilation to all traditional dark-target surfaces. This development includes the evaluation of the current state of satellite aerosol measurements over land relative to the accuracy requirements of the Navy Aerosol Analysis and Prediction System. This work is tightly integrated with the over-water data assimilation development and long-term simulation work on a parallel ONR grant to Prof. Jianglong Zhang at the University of North Dakota (UND). Status: Completed, peer review paper submitted.

- Initiate a program to develop error matrices and spread functions for the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) data to use in refining aerosol vertical information. Status: NAAPS specific CALIPSO product has been created and tested in a 3-D variational analysis scheme in both NASA version 2 and now version 3 data products. This work has resulted in one submitted publication and several in preparation.

- Improve the aerosol source and sink descriptions in the model used operationally by the Navy. Status: This project completed a 10 year re-analysis from which improvements to both the wet and dry deposition have been made. Further, we completed our preliminary investigation of the impact of using a satellite-based precipitation scheme. This work resulted in two publications.

- In collaboration with Dr. James Hansen, intiate an ensemble based data assimilation program in both global and meso-scales. The COAMPS dust module has been ported to the NCAR Data Assimilation Research Testbed (DART). Using the Sahara as a test region, we explored the use of ensemble methods to contrain regional dust source functions.

APPROACH

Work performed in FY10 focused on the development of prognostic error models for MODIS over-land data and our internal CALIOP/CALIPSO product. We also investigated the use of other relevant satellite products such as high-resolution precipitation products and satellite-model innovation vectors to assess deficiencies in sink and source terms.

The typical method for satellite evaluation is through high-precision aerosol measurements from the global AERONET monitoring network, coupled with land surface products for albedo and snow. These were used to perform a detailed evaluation of the MODIS version 5 aerosol optical depth (AOD) retrieval over land areas. In the final year were explored the use of satellite-to-satellite comparisons (e.g. to MISR) to help further refine spatially and temporally correlated bias fields. After identifying and quantifying uncertainties in retrieved AOD as well as performing empirical corrections and data screening methods, we developed further refined prognostic error modeling.

For CALIPSO, a similar process was performed. However, the lack of substantive vertical information to validate lidar data makes the process much more complex. In response, we are working closely with the CALIPSO project team at NASA Langley. We are combining Navy and NASA field data along with representative CALIPSO data to develop a suitable calibration/validation data set. In order to ensure consistency with the model, a system which utilizes NAAPS AOD fields to help constrain the lidar ratio in the lidar extinction retrieval has been derived. In the middle of FY10 a new version of the CALIOP aerosol product was released and required examination. Our early results show that this product is a marked improvement.

As components of the satellite products/assimilation system are completed, we have begun the feedback process on improving source functions. Since the assimilation process requires a reasonable first guess by the model, several iterations between model analysis and observations over large time series are required to optimize the system. To this end, we created a 10 year model reanalysis product. In the final year, we compared innovation vectors to source/sink terms in the model. In particular we were interested in refining NAAPS dry deposition velocities, as this appears to be a controlling term in boundary layer aerosol particle concentrations.

Finally, we wished to examine in detail the spatial and temporal correlation lengths of observation information content. To this end we entered into the field of ensemble based data assimilation. In FY10, COAMPS was ported to the NCAR *Data Assimilation Research Testbed (DART).* DART works as a community facility for the promotion of ensemble–based data assimilation research. Developed and maintained by the Data Assimilation Research Section (DAReS) at NCAR, DART provides tools that can be customized to support efficient operational DA applications. By jointly funding a postdoctoral researcher (Vikram Khade) with James Hansen of the NRL Predictability Research Office, we ran a series of COAMPS simulations with DART and MODIS Deep Blue to examine dust source sensitivities to erodibility fraction, friction velocity, and threshold wind speed.

WORK COMPLETED

Over FY10, focus has been on the incorporation of satellite products into the NAAPS model. Areas of work can be categorized under:

a) Prognostic error modeling: Based on our evaluation of the MODIS over land aerosol product and the subsequently derived data assimilation grade product, we developed a point-wise prognostic error model for use in data assimilation which accounts for regional land surface and microphysics.

b) Lidar product development: Based on a combination of NAAPS and CALIPSO data, a level 3 lidar product from the CALIOP version 3 reprocessing for the year 2009 has been generated for use in 3D variational data assimilation systems such as NAVDAS-AOD.

c) 10 year re-analysis: To fine tune the NAAPS smoke emissions algorithm, a ten year reanalysis has been completed in data assimilation modes which includes both MODIS and MISR assimilation.

d) Porting of COAMPS dust modeling to the *Data Assimilation Research Testbed* and performance of perfect model and MODIS Deep Blue simulations.

e) IR Dust properties: Based on advanced IR models, we examined the impact of particle shape and composition on the mass scattering and absorption transfer function between visible and IR wavelengths.

RESULTS

This project encompasses a number of sub-projects aligned with the work completed listed above. Key results are as follows:

<u>*Prognostic error modeling (Hyer and Reid):*</u> Uncertainty in the gridded MODIS AOD data was estimated using the linear estimation of Root mean Square Error (RMSE) as a function of AOD, and a

“noise floor” RMSE used as a minimum value. Parameters of the uncertainty estimation for regions over the globe with sufficient data volume were calculated for both natural and our QA’d versions of data. An example of global area uncertainty is shown in Figure 1. Data assimilation grade QA, while a definite improvement over the majority of the globe is not as dramatic as similar efforts for the over water. This owes to the complicated error terms which drive uncertainty in over land retrievals (complex BRDF, microphysics, drop in differential signal to noise, etc.). However, with these improved error models, the data assimilation system can make best use of effective data.

Lidar product development (Campbell): The previous year, a method was generated for constructing one-degree along-track and cloud-free signal composite averages that is consistent with Navy Aerosol Analysis and Prediction System (NAAPS) model gridding, using CALIOP Level 1B attenuated backscatter and Level 2 cloud boundary-height products. In FY10, this production was repeated for the new CALIOP version 3 product generated by NASA. The entire year of 2009 was acquired, processed and tested within the NAVDAS-AOD 3D-var scheme being developed by Dr. Jianglong Zhang at the University of North Dakota. An example of the assimilation process is presented in Figure 2. The process begins with the original NAAPS MODIS 2DVar AOD assimilation. The resulting AOD analysis is then used to constrain the lidar retrieval based on the CALIOP backscatter profiles. These are then in turn assimilated in 3DVar back into the model for the final analysis. Even though the retrieval is constrained by NAAPS AOD, we found that through the proper redistribution of aerosol particles in the 3DVar step, forecasts in AOD are improved by 15%.

10-Year Reanalysis (Xian-ASEE, Sessions-CSC, and Reid): Though a two-year reanalysis was conducted in the previous year, in FY10 we expanded this to the entire 10 year satellite data record. This gave us the opportunity to evaluate data sets and model output over inter-seasonal time frames. Used primarily as an evaluation tool, we kept track of statistics on assimilation innovations in order to identify areas of improvement in model source and sink functions. An example of a monthly average innovation is presented in Figure 3. Clearly visible is NAAPS over production of smoke and dust in Africa, followed by a general over deposition of aerosol particles over the ocean. Corrections to these terms are nearly complete.

COAMPS in DART (Khade-UCAR): In the final year of this project we wished to explore the application of ensemble methods for data assimilation. After the porting of COAMPS and its dust module to DART, we embarked on a key sensitivity study to assess what observations are required in order to invert source functions. An example of a perfect model simulation over 4 days trying to reproduce the NAAPS source function “errodability fraction” assuming 6 hour assimilation is presented in Figure 4. Using perfect model studies, we found that the “once daily” products such as are available from polar orbiters are not sufficient to invert source functions. Rather, geostationary methods are likely necessary. Such work is in a pending proposal.

Dust IR Properties (Hansell-GSFC and Reid): A key uncertainty in the application of NAAPS data to infrared problem is the formulation of appropriate optical models for dust. The community has taken two separate paths in this regard. Most have moved towards spheroidal models to represent complicated dust shapes. Others have used discrete shapes. To understand the sensitivities and impacts in NAAPS spectral AOD fields we performed a sensitivity study to the most common mineralogies and shape factors used in the field. An example calculation is presented in Figure 5. Most interestingly, the two basic methods in the field depart from the sphere model in opposite directions. Until actual measurements are made in the IR, continuing with a spherical model may be most prudent.

IMPACT/APPLICATIONS

The AOD datasets we have produced will allow us to directly test the forecast impact of different choices; balancing aggressive data filtering with avoiding unnecessary reduction in data volume and coverage. Once the tradeoffs have been quantified, we can begin to incorporate over-land AOD observations in the NAVDAS-AOD system, thereby improving forecast skill over both land and ocean. Once fully implemented, it will be considerably easier to add additional sensors and sustain long-term support of the system. Further, with the substantially improved model efficacy that data assimilation provides, it will be possible to predict higher level radiation fields, directed energy impacts, and EO propagation in both the global, and eventually mesoscale models.

TRANSITIONS

Code for optical depth data assimilation and NAVDAS-AOD has been delivered to FNMOC through a 6.4 SPAWAR project for operations.

RELATED PROJECTS

This project is tightly coupled to a number of ONR 32 programs, particularly those of Professor Jianglong Zhang at the University of North Dakota. Our primary transition partner is Douglas Westphal, who is principal investigator on the Large-Scale Aerosol Model Development (PI: Doug Westphal). New data-processing and visualization systems are being adapted for aerosol research through the COAMPS-On Scene(COAMPS-OS®)[2] IVPS charts program (PI: John Cook). We have also begun working with Jim Hansen on his ONR -funded project for the use of ensemble data assimilation in the prediction of atmospheric constituents.

PUBLICATIONS

Campbell, J. R., J. S. Reid, D. L. Westphal, J. Zhang, **E. J. Hyer**, and E. J. Welton, 2010: CALIOP aerosol subset processing for global aerosol transport model data assimilation, *J of Sel. Topics in Appl. Earth Obs. and Rem. Sens., 3,* 203-214. [published, refereed].

Fisher, J. A., Jacob, D. J., Purdy, M. T., Kopacz, M., Le Sager, P., Carouge, C., Holmes, C. D., Yantosca, R. M., Batchelor, R. L., Strong, K., Diskin, G. S., Fuelberg, H. E., Holloway, J. S**., Hyer, E. J.,** McMillan, W. W., Warner, J., Streets, D. G., Zhang, Q., Wang, Y., and Wu, S., 2010: Source attribution and interannual variability of Arctic pollution in spring constrained by aircraft (ARCTAS, ARCPAC) and satellite (AIRS) observations of carbon monoxide, Atmos. Chem. Phys., 10, 977-996. [published, refereed].

Hansell, R. A., S. C. Tsay, Q. Ji, N.C. Hsu, M.J. Jeong, S.H. Wang, **J. S. Reid**, K. N. Liou, S. C. Ou, 2010: Assessments of surface longwave radiative effects by airborne Saharan dust during the NAMMA field campaign, *J. Atmos. Sci., 67,* 1048-1065. [published, refereed].

[2] COAMPS-OS® is a registered trademark of the Naval Research Laboratory.

Hyer, E. J., and Chew, B. N., 2010: Aerosol transport model evaluation of an extreme smoke episode in Southeast Asia, Atmos. Environ., 44, 1422-1427, doi:10.1016/j.atmosenv.2010.01.043. [published, refereed].

Reid, J.S., E. J. Hyer, E. M. Prins, et al., 2009: Global monitoring and forecasting of biomass-burning smoke: Description and lessons from the Fire Locating and Modeling of Burning Emissions (FLAMBE) program, *J of Sel. Topics in Appl. Earth Obs. and Rem. Sens, 2,* 144-162. [published, refereed].

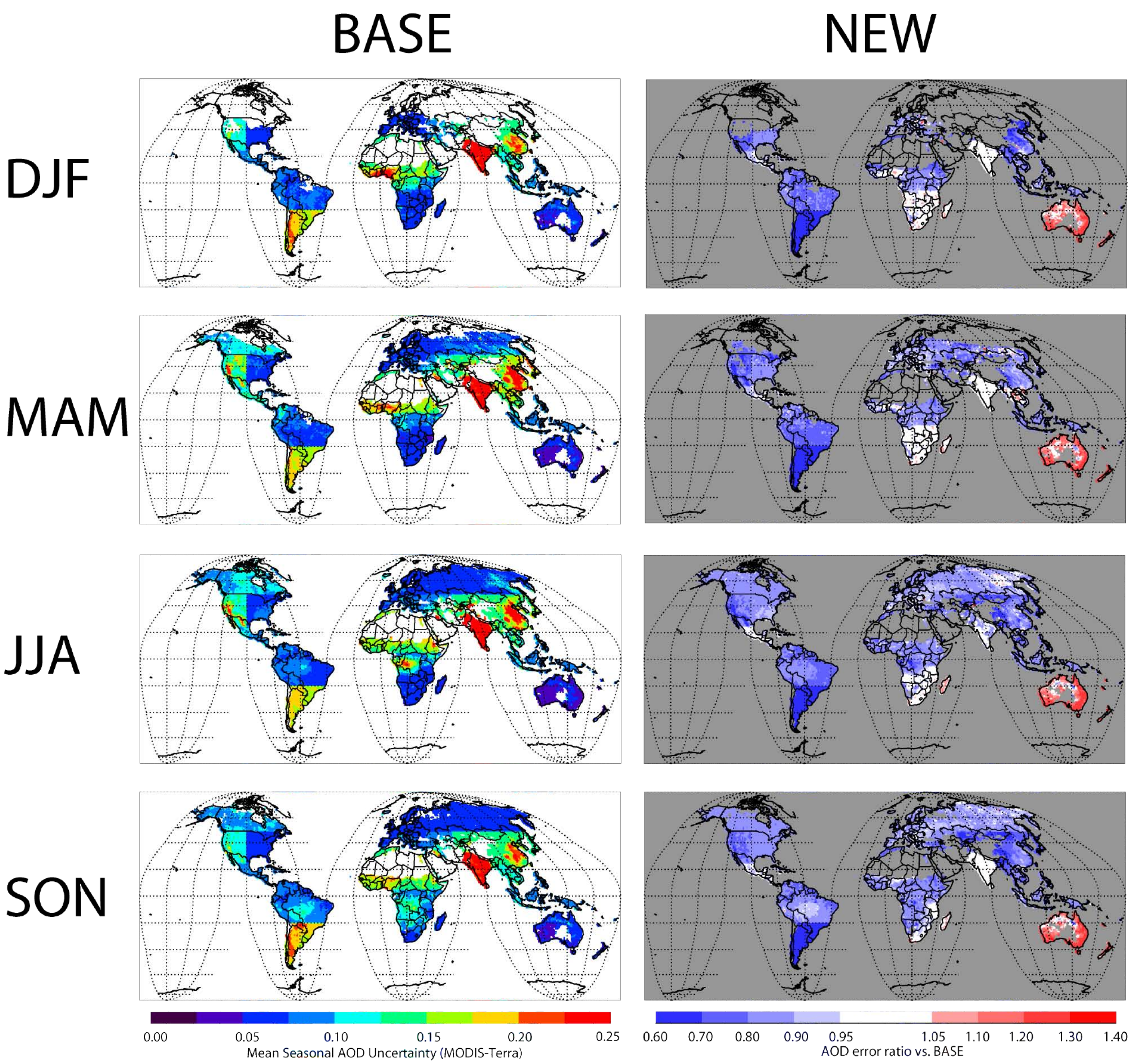

Figure 1. Mean estimated uncertainty in AOD for 1-degree grid cells. The left column shows the mean uncertainty estimated for the BASE scenario using the prognostic error model. The right column shows the ratio of the mean uncertainty for the NEW scenario used for assimilation to the BASE scenario. Rows indicate different seasons. Data used were from MODIS-Terra for the period December 2007 – November 2008.

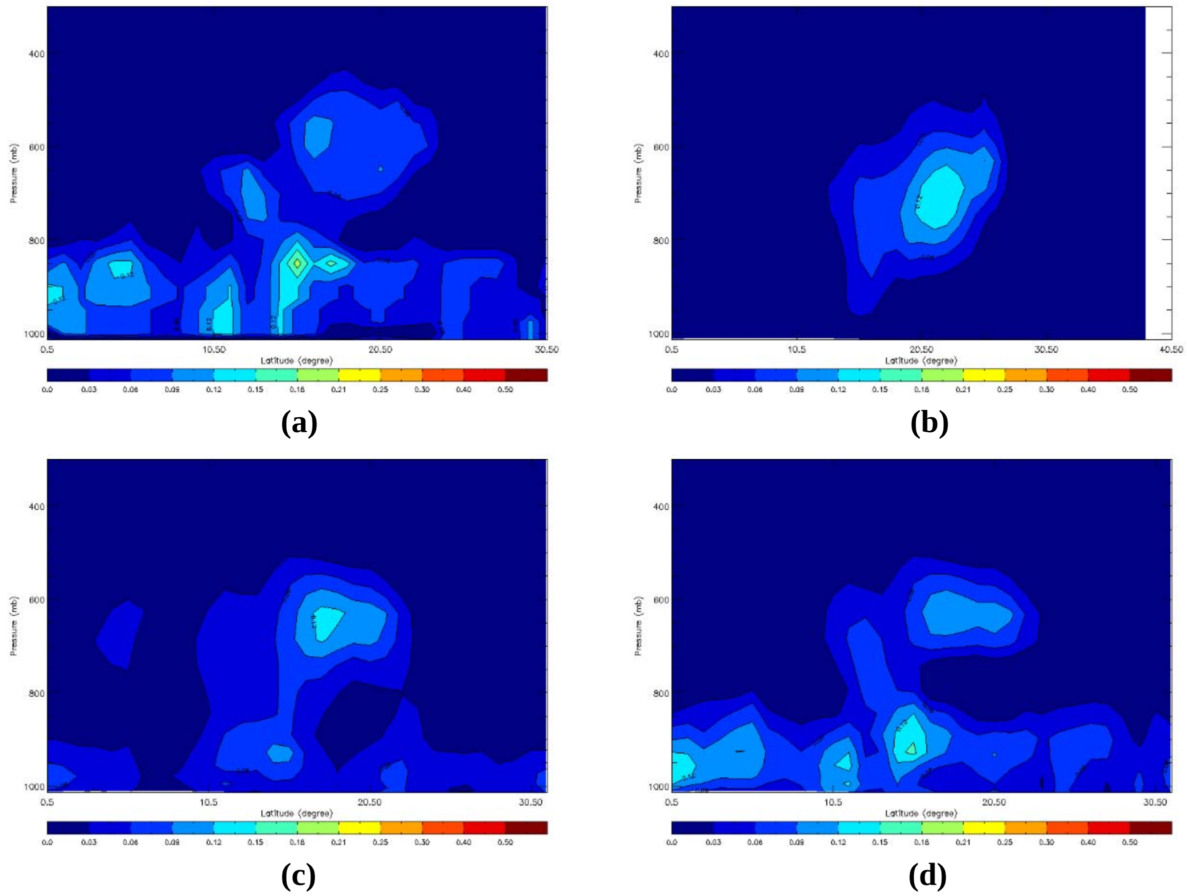

Figure 2. (a) CALIOP 0.532 µm extinction coefficient (1/km; see text) for ~1800 UTC granule segment between 0 - 30º N 20 July 2007 at 1º along-track and 0.100 vertical resolutions; (b) corresponding NAAPS output after 2D-VAR assimilation of MODIS and MISR data only; (c) corresponding NAAPS output before consideration of data in (a), but after "spinning" model up for two weeks prior using 3D-VAR; (d) final corresponding NAAPS profile after 3D-VAR considering data in (a).

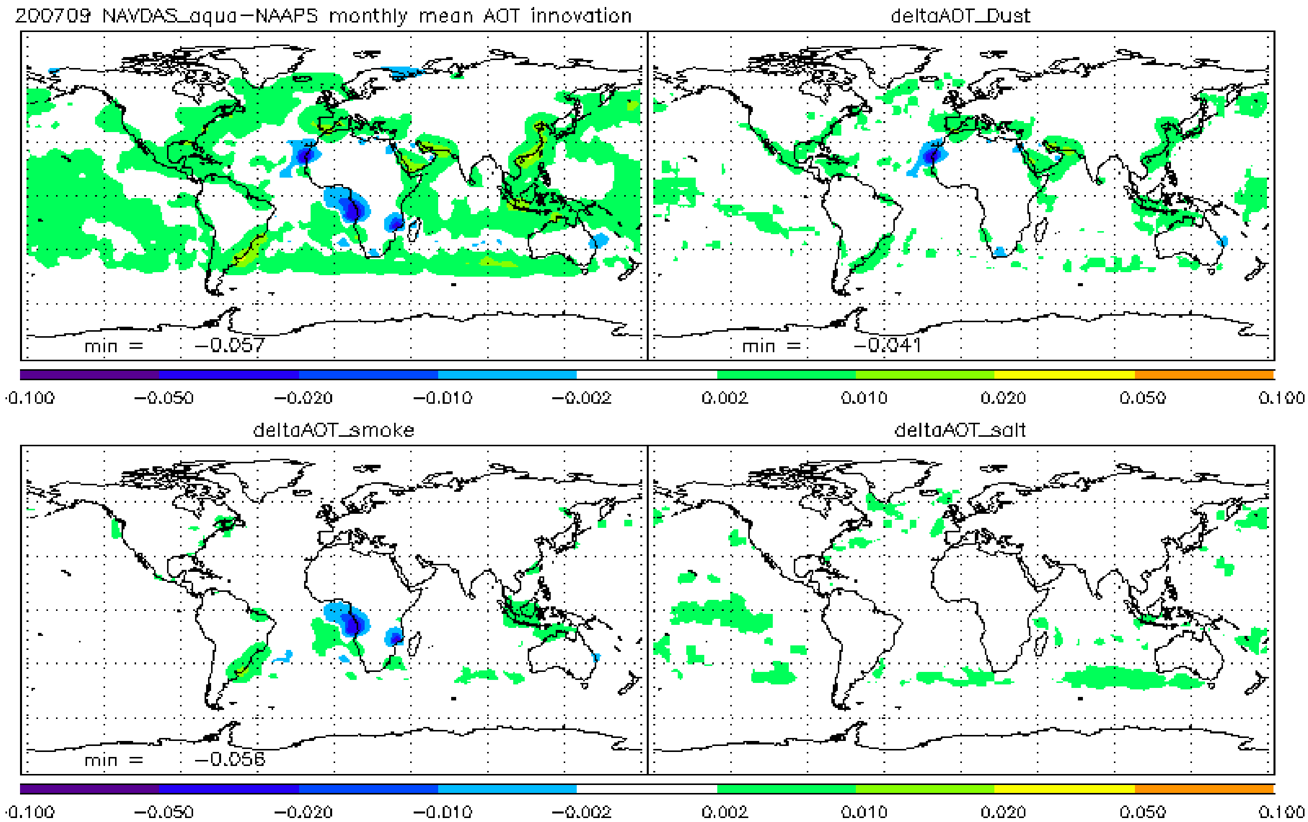

Figure 3. Example of monthly mean MODIS (ocean)-NAAPS innovation for total AOD (upper left), for dust (upper right), smoke (lower left) and sea salt (lower right).

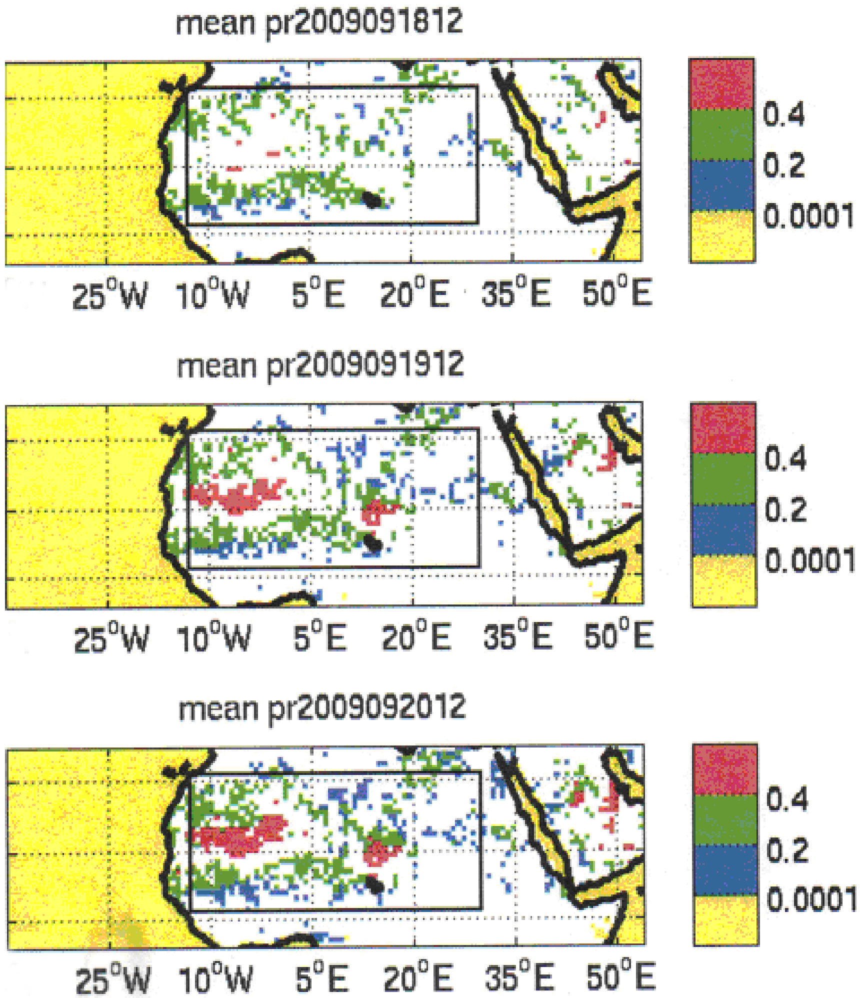

Figure 4. Output from a perfect model simulation in COAMPS-DART of dust source erodability fraction development after 3 days of simulation with assimilation every 6 hours.

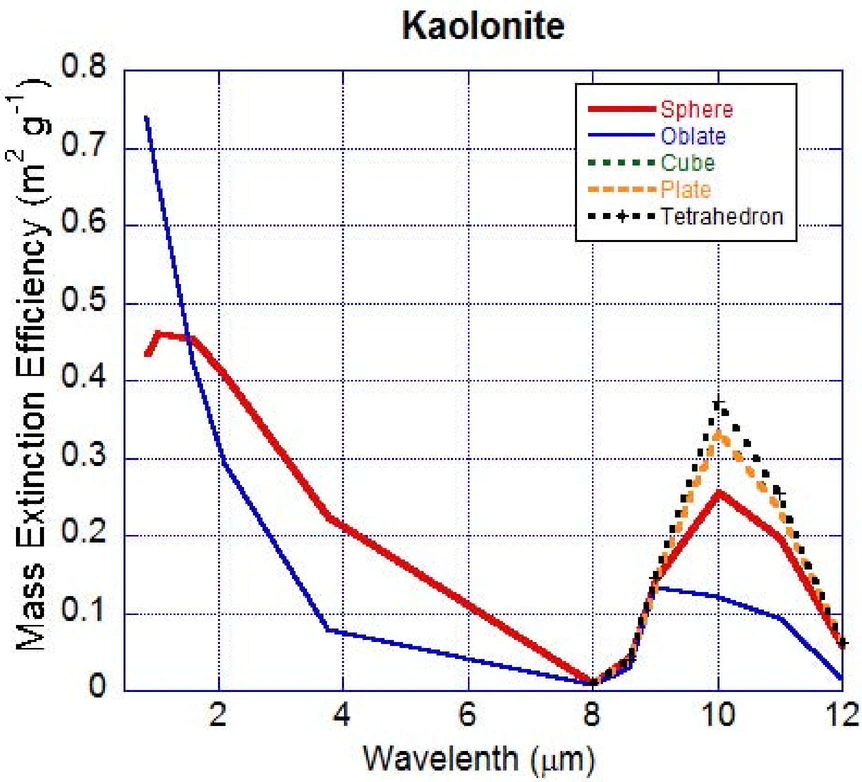

Figure 5. Calculated spectral mass extinction efficiency for the common dust mineral Kaolinite as a function of particle shape representation. Notice the opposite sign sensitivity as a function of spheroid versus direct object representation.